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POSSIBLE OBSERVATIONAL CRITERIA FOR DISTINGUISHING BROWN DWARFS FROM PLANETS

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ABSTRACT

The difference in formation process between binary stars and planetary systems is reflected in their composition, as well as orbital architecture, particularly in their orbital eccentricity as a function of orbital period. It is suggested here that this difference can be used as an observational criterion to distinguish between brown dwarfs and planets. Application of the orbital criterion suggests that, with three possible exceptions, all of the recently discovered substellar companions may be brown dwarfs and not planets. These criterion may be used as a guide for interpretation of the nature of substellar-mass companions to stars in the future.

Subject headings: binaries: spectroscopic — planetary systems — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

It is not unusual in science to find that the initial early detection of a phenomenon is followed by a rapidly increasing discovery rate as interest intensifies and new technology is developed. Such has been the case with the search for substellar companions to stars in the solar neighborhood. While there have been claims of detections of companions to stars with masses less than the lower limit for the mass of a star,[1] most have not stood the test of time. However, that has changed following the announcement of the detection of a companion to the star HD 114762 (Latham et al. 1989). During the interval of time from 1995 to early 1997 there have been reported detections of 20 substellar-mass companions to nearby stars.

The recent avalanche of detections began with the paper announcing the discovery of a companion to the star 51 Peg (Mayor & Queloz 1995). The lower limit to the mass of the companion is 0.45 M_J. More remarkable than the mass of the companion was its orbital period, 4.23 days. The semimajor axis of this companion is only 0.05 AU! The detection of the radial velocity variation for 51 Peg was confirmed, and there began a rapid sequence of detections of what have been called by their discoverers "extrasolar planets."

But, are these companions really planets? On what basis was that interpretation of the data made, and how firm is it? Could these objects be something else, like the bottom end of the star formation process, viz., brown dwarfs, or an as yet unidentified class of astronomical object? Indeed, there is now a serious challenge (Gray 1997) to the interpretation that the 51 Peg signal is due to a companion of any kind. It may be that all of the short-period signals that have been attributed to planetary companions may be intrinsic to the star, but that will become clear with additional observations of the type conducted by Gray. The criteria suggested here do not depend upon the reality of those companion systems.

The fundamental distinction between brown dwarfs and planets is the manner in which they are formed (e.g., Kaftos, Harrington, & Maran 1986). Brown dwarfs are formed in the same manner as a star, which means that if they are found as companions to stars then they were formed by the process that formed the binary star system. The underlying mechanism in

that case is not fully understood, but is thought to involve large-scale gravitational instabilities. Planets, at least the nine that we can study in detail, in contrast, appear to be formed by an accretion process beginning from small dust grains building up to planetesimals to lunar-sized objects to terrestrial planet-sized objects and then, depending on the availability of gas, to giant gas-rich planets such as Jupiter.

Thus, the distinction between brown dwarfs and planets is fundamental. It is not a "matter of semantics." An incorrect identification of the nature of these companions would lead in turn to erroneous notions about the basic processes involved in their formation and evolution. It is important to note that, as we do not at this time know either the lower limit to the mass of a brown dwarf or the upper limit to the mass of a planet, one cannot at this time use mass alone as the basis for identifying a given companion to a star as a planet, unless the mass is well below likely masses for brown dwarfs (i.e., Earth-mass companions).

The substellar-mass companions discovered since 1989 are listed in Table 1. There are two exceptions. The companion to HD 98230 was discovered, or at least the observations made, in 1931 (Bergman 1931). Also, the Table lists only those companions discovered by radial velocity observations. The possible companion(s) to Lelande 21185 (Gatewood 1996) are not included, as there is no reliable estimate at present of their eccentricity.

2. AN ORBITAL SIGNATURE OF FORMATION PROCESS

The observational criterion suggested here for distinguishing between brown dwarf and planetary companions to a star concerns the relationship between two properties of the companion's orbit, namely, its eccentricity as a function of its period. Figure 1 shows orbital eccentricity versus the logarithm of orbital period, expressed in days, for two populations. One population is pre–main-sequence (PMS) binaries (Mathieu 1994). Another is objects thought to have formed via accretion in a disk, the giant planets in the solar system. Note that low eccentricity is a characteristic for other objects such as the terrestrial planets, the regular satellites of the giant planets in the solar system, and the companions to the pulsar PSR 1257+12 (Wolszczan & Frail 1992), all of which are thought to have formed by accretion from a disk.

Data for PMS binaries were used, as they presumably reflect any signature of the binary formation process with minimal

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[1] Roughly 80 Jupiter masses (M_J). Normally these masses are expressed in terms of solar masses, but the mass of Jupiter is a more appropriate unit for this discussion.

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TABLE 1

PROPERTIES OF NEWLY DISCOVERED SUBSTELLAR COMPANIONS

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Star	Mass	Period (days)	Eccentricity	References
51 Peg	0.45	4.23	0.00	1
ν And	0.65	4.61	0.11	2, 3, 4
55 Cnc	0.84	14.65	0.05	2, 3, 4
ρ CrB	1.1	39.64	0.03	5
16 Cyg	1.6	804	0.65	6
47 UMa	2.3	1090	0.08	2, 3, 4
τ Boo	3.9	3.31	0.00	2, 3, 4
70 Vir	7.4	116.7	0.37	2, 3, 4
HD 114762	9.0	84.02	0.33	7
HD 110833	17	270	0.69	8
BD −04°782	21	240.92	0.28	8
HD 112758	35	103.22	0.16	8
HD 98230	37	3.98	0.00	9
HD 18445	39	554.67	0.54	8
HD 29587	40	1471.70	0.37	8
HD 140913	46	147.94	0.61	8
BD +26°730	50	1.79	0.02	8
HD 89707	54	298.25	0.95	8
HD 217580	60	454.66	0.52	8

REFERENCES.—(1) Mayor & Queloz 1995; (2) Butler & Marcy 1996; (3) Butler et al. 1998; (4) Marcy & Butler 1996; (5) Noyes et al. 1997; (6) Cochran & Hatzes 1996; (7) Latham et al. 1989; (8) Mayor et al. 1996; (9) Bergman 1931.

alteration. Also, only systems with periods less than 10^4 days were used because of the apparent difference in the mass function for this class of companions as compared with field stars and companions with periods longer than 10^4 days (Abt & Levy 1976; Mazeh et al. 1992). This difference has been taken as evidence by these authors and by Mathieu (1994) that the formation process for short-period binaries differs from that for field or long-period companions (see also Trimble & Cheung 1976; Trimble 1990). Main-sequence binaries with periods in the range considered here display a similar (e, log P) distribution, as do the PMS binaries. Orbital evolution is thus not likely to be a major consideration for periods much beyond a few weeks. Furthermore, it appears that the (e, log P) distribution is established early in the history of these systems (Mathieu 1994), consistent with a signature of their formation.

The distribution of (e, log P) for stellar companions is markedly different from that for planetary companions. This difference is a reflection of a corresponding difference in the manner by which objects in these two classes were formed. A least-squares fit to the binary star distribution gives e = 0.2 log P − 0.03. This yields a Pearson correlation coefficient of r = 0.76. This statistical test suggests that the causal relationship between eccentricity and period is a modest but significant one. While a trend is clear, there is a range of eccentricities at a given period.

3. A TEST OF THE CRITERION

If the proposed (e, log P) criterion is valid, one expects that the (e, log P) distribution for binary brown dwarfs would mimic, if not be indistinguishable from, that shown in Figure 1. Ten of the companions in Table 1 have $17 \lesssim M_c \sin i \lesssim 80$, and as such are likely to be brown dwarfs.

The (e, log P) set for those 10 companions has a Pearson coefficient r = 0.67. This is similar to that for PMS binary companions. The least-squares fit for the data gives e = 0.22 log P − 0.05, indistinguishable from that of PMS binaries given the uncertainties in the coefficients.

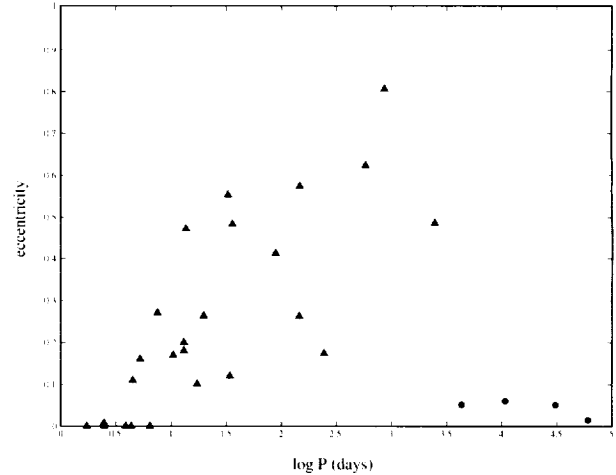A better measure of the reality of these correlations is the

FIG. 1.—Orbital eccentricity as a function of orbital period in days for two populations, pre–main-sequence binary stars (filled triangles; Mathieu 1994) and giant planets in the solar system (filled circles).

Spearman coefficient as it is derived from a simple ranking of the data and does not depend on knowing the distribution function that might underlie the data (e.g., normal bivariate). The Spearman coefficient for the brown dwarf companions is ρ = 0.58. This suggests that the correlation between e and log P for this group of 10 systems is significant at the 95% level.

It is clear from the above that the orbital signature of formation is the same for PMS binaries and the brown dwarf companions; this demonstrates the validity of the criterion.

4. APPLICATION OF THE CRITERION

We now apply the criterion to the group of substellar companions listed in Table 1 with $M_c \sin i \lesssim 10$. The least-squares fit gives e = 0.14 log P − 0.04. This is similar to, but differs from the best fits to the PMS and brown dwarf populations. The Pearson coefficient for this group is r = 0.63, and the Spearman coefficient is ρ = 0.73.

It should be noted that the results for this group are skewed heavily by two systems, 47 UMa and ρ CrB. If these two systems are ignored, and there is no a priori justification for so doing, the remaining systems yield a best fit of e = 0.23 log P − 0.10. This gives values of e at a given value of log P that are in good agreement with the values calculated from the best-fit lines for PMS and brown dwarfs. The Pearson coefficient for this fit is r = 0.95, and the Spearman coefficient is ρ = 0.96. This trend is both statistically significant and consistent with that of the PMS binaries and brown dwarfs.

5. DISCUSSION

Shown in Figure 2 are all three populations, PMS, brown dwarfs, and companions with $M_c \sin i \lesssim 10$. Also shown for reference is the best-fit line for the combined population. The Spearman coefficient for the three populations combined is 0.75. With a sample consisting of 44 members, this value of the Spearman coefficient indicates that the observed correlation is significant at greater than the 99.999% confidence level.

It would appear that with two exceptions, a third if we include the astrometric system LeLande 21185, all of the newly discovered, substellar-mass companions, have an (e, log P) distribution that could be drawn from the same population, and
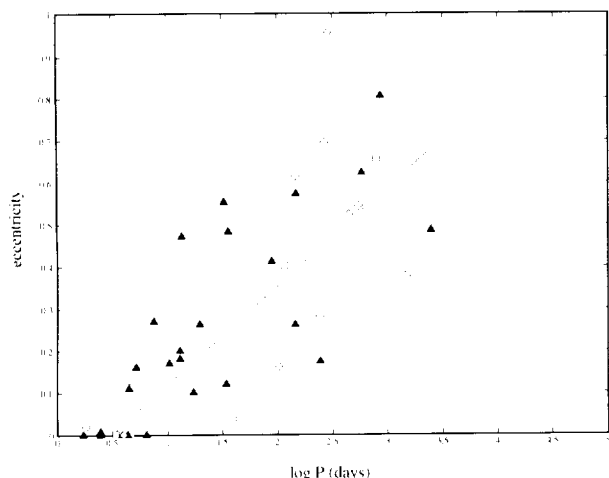
log P (days)

Fig. 2.—Same as Fig. 1, but for three populations. Pre–main-sequence binary stars (*filled triangles*), companions with minimum masses greater than 10 but less than 80 M_J (*open diamonds*; Mayor et al. 1996), and companions with minimum masses less than 10 M_J (*open squares*; Latham et al. 1989; Mayor & Queloz 1995; Marcy & Butler 1996). Also shown for reference is the best-fit line for the combined populations.

that this distribution is indistinguishable from that of PMS binary companions. Given that this distribution is a signature of their formation process, it would appear that these companions formed by the same process as the binary stellar companions. That is, those companions display the orbital signature of brown dwarfs and not that of planets.

Some authors (e.g., Butler et al. 1998) have suggested that companions with low eccentricity, such as the putative companion to 51 Peg, are planets by virtue of their low eccentricity. However, as is clear from Figure 1 and knowledge of tidal effects (e.g., Duquennoy & Mayor 1992), any companion that is that close to a star will be in a low-eccentricity orbit. The substellar companions with short periods are fully consistent with them being members of the stellar population. For any companion that has a sufficiently short period that its orbit will be tidally circularized, its eccentricity alone cannot be used as a criterion for identifying it as a planet.

There is an additional orbital signature that could be useful as a criterion to determine whether a companion is a planet (Black 1980). This arises again from the formation mode, namely, more than one companion is formed and the resultant orbital architecture is characteristic of that process, and that architecture differs from that of a multiple star system. The regular satellite systems of Jupiter, Saturn, and Uranus, as well as the companions to the pulsar PSR 1257+12, and the planets in the solar system are all multiple systems with geometric spacing of the orbits. The five systems that we have reason to believe have companions formed by accretion all have the same basic architecture. If the companions that have been discovered are planets, one can expect that other companions are present. So far, no such companions have been found. Their continued absence would weaken the interpretation of the companions in Table 1 as planets, whereas detection of such companions strengthens that interpretation.

Nature knows how to make even stellar mass companions with short orbital periods, so if these objects are brown dwarfs, their presence close to the star is not a mystery, but is to be expected. Also, the high eccentricities that are seen for the putative planets with orbital periods longer than a few weeks

is perfectly natural if they are brown dwarfs. For example, given the orbital period of the companion to 16 Cyg B, the best-fit line *based just on the PMS binary star distribution* would predict an eccentricity of 0.55 for the companion. The observed eccentricity is 0.65, good agreement given the uncertainty in both the fit and the data. Similarly, the predicted eccentricity for the companion to 70 Vir is 0.38, virtually identical with the observed value of 0.37. The fit is even better if one uses the regression defined by all the data points shown in Figure 2. There is no need to postulate a form of dynamical instability arising from the presence of a distant binary to account for the observed eccentricity (e.g., Holman, Touma, & Tremaine 1997; Innanen et al. 1997). Indeed it is problematic whether the proposed mechanism would work in the presence of a system where there are other sources of gravity such as other companions, as would be the case if the companion is a planet, or a disk, in the vicinity of the companion to 16 Cyg. This caveat is pointed out by both Holman et al. (1997) and Innanen et al. (1997). There is no binary in the case of 70 Vir to cause the eccentricity of this companion, so if it is a "planet," one must invoke yet another mechanism. The binary formation mechanism would appear to provide a single, unifying context for the observed orbital eccentricities and their systematic variation with orbital period.

The interpretation of the nature of the newly discovered substellar companions that emerges from the (e, log P) criterion also removes the need for mechanisms (Lin, Bodenheimer, & Richardson 1996; Trilling et al. 1996; Weidenschilling & Marzari 1996) that postulate significant (i.e., nearly unity fractional change in semimajor axis) orbital evolution to account for short-period companions. It should be noted that contrary to statements elsewhere (e.g., Marcy & Butler 1996) the location of the apparent companion to 47 UMa has not been shown to be inconsistent with where a giant planet might form based upon our current paradigm for gas giant planet formation. The companion to ρ CrB, if it is a planet, would likely have experienced orbital migration, but an alternative interpretation is that it is a brown dwarf, formed near its current location, with a slightly lower eccentricity than is typical for such companions with that orbital period.

This does not mean that such mechanisms cannot, or do not, occur in planetary systems, but there is no independent evidence that such large-scale migration occurs in those disks that end up making planetary systems. On the contrary, the five bona fide systems where it is believed that accretion-formed companions exist all show no signs (e.g., eccentric and non-geometric spaced orbits) of such motion. It will be important to understand the *testable*, that is observable, consequences of models that suggest that systems such as 51 Peg are the result of large-scale motion through a disk. Clearly, one such observable test for those models that rely upon gravitational scattering of one giant planet by another would be the presence of a second companion in a very high-eccentricity, longer period orbit. Failure to find such companions would rule out such models. Models that rely solely on interactions between a single large planet and its parent disk are more difficult to verify by examining only their end state. Their verification will likely await instruments capable of very high spatial resolution far-infrared to submillimeter studies of young systems where the possible detection of density waves in such disks could signal that the process in question is taking place.

Another observational criterion for distinguishing between brown dwarfs and planets was suggested originally by Lunine (1986) and refined recently (Saumon et al. 1996). The basic

notion is that as planets form via accretion with solid material playing a key role, one expects that the abundance of metals relative to hydrogen will be greater than in the central star. That is the case for Jupiter relative to the Sun. In contrast, as a brown dwarf is formed by the same process as a star, one expects that the composition of a brown dwarf companion will be similar to, if not identical with, that of its stellar companion. A spectroscopist confronted with two Jupiter-mass objects, one a planet and the other a brown dwarf, should be able in principle to distinguish which is which on the basis of the metal-to-hydrogen ratio normalized to the same ratio in the central star. Spectroscopic studies of companions to other stars are beyond the capability of existing instruments except for situations where the companion is both relatively luminous and well separated from its stellar companion. Thus, while this observational test has potential, its full application must also await future instrumentation.

The perspective offered here raises the important point that these new detections are providing the first observational guide to the lower limit to the mass of a brown dwarf. Assuming that there is nothing pathological in the viewing geometry for these systems (i.e., $\sin i \sim 0$), then it would appear that the lower limit is comparable to the mass of Jupiter. It will be interesting to see whether even less-massive companions are discovered with short orbital periods. Systems with the accuracy of those now in use should be able to detect companions with masses as low as a few tens of Earth masses in orbits with periods of a few days.

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